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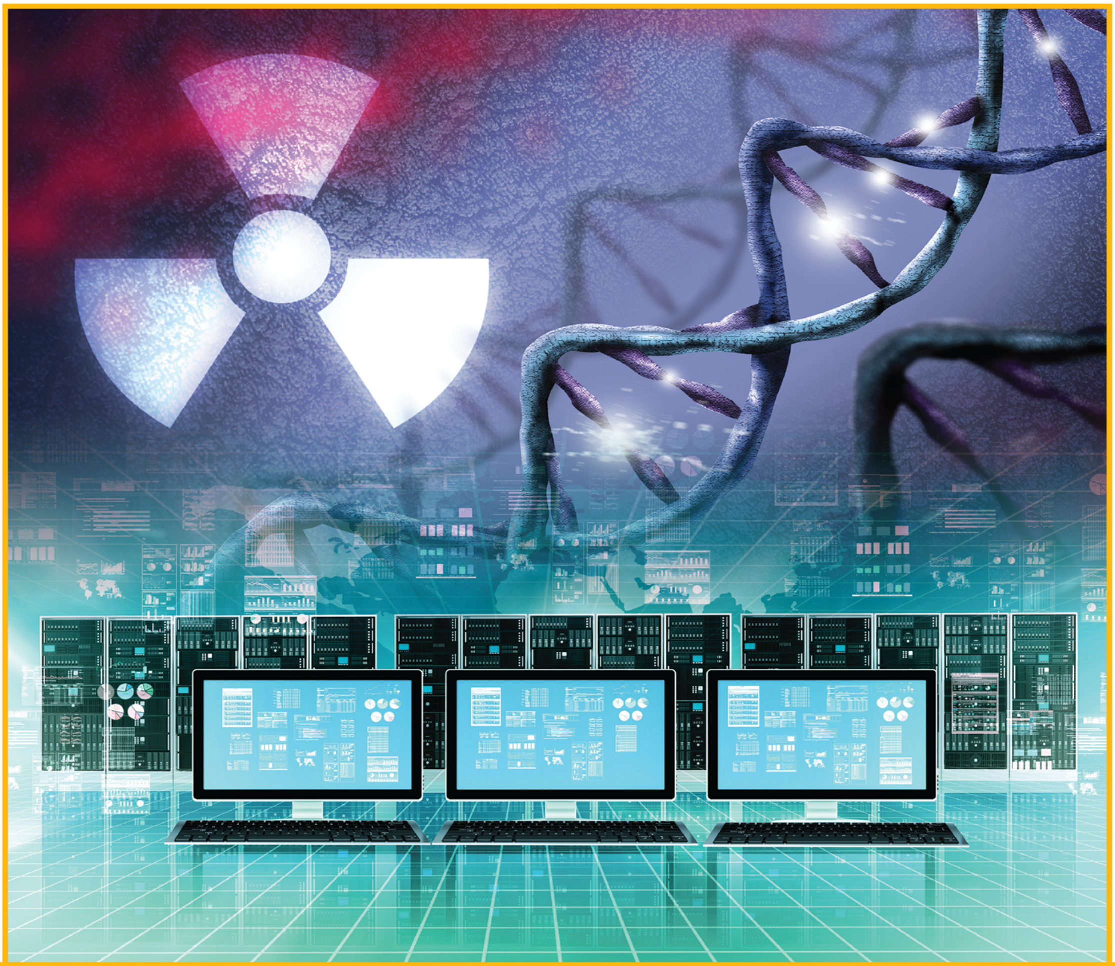

Siyong Kim • John Wong

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Advanced and Emerging Technologies in Radiation Oncology Physics

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Preface

These days, it is not unusual to frequently realize how fast technological change does occur. For example, even a law that the doubling of computer processing speed happens every 18 months—known as Moore's Law—does exist in the area of computer science. The field of radiation oncology physics is not an exception and has recently experienced significant technological developments. Such rapid change is expected to be continued even with higher speed. As commonly agreed, medical physics is the driving force in adapting new technologies in radiation therapy. Thus, it is desirable for physicists to be continuously up-to-date in technical aspects, and this book describes advanced and emerging technologies in radiation oncology physics. The main intention of the book is to help medical physicists get proactively prepared for advanced and emerging technologies so that such technologies, when become available for their clinic, can be implemented properly and efficiently to maximize the benefit patients would get from them. In addition, this book is expected to provide important information to both students and researchers that would help them timely find their research topics and directions.

In alignment with the main intention, chapters of this book has been grouped in five based on their topic. Brachytherapy is an important part of radiation therapy but was intentionally excluded in this book.

1. *Topic I—Imaging*: New technologies in imaging physics that are under early-test or have great potential for radiation therapy are mainly described under this topic. To cover the wide range of imaging modalities (e.g., CT, MR, and PET) and related biological modeling, a total of four chapters are allocated under this topic.
2. *Topic II—Treatment planning*: Enhancing computer power is a continuing subject of research and recent architectural advances such as GPU-based computing and cloud-based computing can bring significant benefit for radiation therapy. This topic deals with technological advances in both computer infrastructures and treatment planning algorithms. There are two chapters under this topic.
3. *Topic III—Treatment delivery*: Techniques for setup/target localization in radiation therapy is a unique area and its importance is getting bigger and bigger as more precise delivery within short period time becomes popular. Reviews on both technical improvements in the current systems and new methods in setup/localization are included. When a magnetic resonance imaging unit is integrated

into a treatment unit, it can enhance intra-fraction target monitoring as well as target localization. There are several groups working on such machine, and both the current status and emerging technologies related to those units are described. Interest in charged particle therapy is growing and there is huge effort for improving charged particle therapy system (e.g., super-conducting magnet technology for minimizing unit size), and such developments are described. There are a fair amount of interesting technologies that may not fit into conventional categories but have potential for being useful. One of chapters under this topic describes several of them. Obviously, this is one of major topics and contains four chapters.

4. *Topic IV—Dosimetry, QA, and safety*: Dosimetry is an essential area of radiation therapy, and every new dosimetry technology can make significant impact on routine practice of clinical physics. However, many clinical physicists are not familiar with those methods unless they are directly subject to using such systems. A chapter under this topic describes new developments in dosimetry materials, devices, and systems. Both safety and QA are important subjects in radiation therapy and huge effort is continuously being given on how to enhance them by the radiation therapy societies (e.g., adopting FMEA tool for QA and establishing web-based medical incident reporting systems). Such subjects are dealt with under this topic. Two chapters are included.

5. *Topic V—Informatics*: The importance of informatics in medicine is rapidly growing. One of the outstanding problems in radiotherapy related informatics is how to integrate radiation oncology information into overall medical informatics system. So-called big data is another interesting area, and appropriate utilization of big data has great potential. However, most clinical physicists haven't paid much attention to it. Such issues are described in two chapters assigned under this topic.

There are a total of fourteen chapters in this book. Even though significant effort was made by every author to introduce as many technologies as possible it was practically impossible to handle every technology from every subject. Instead, focus was given on technologies considered either feasibility already demonstrated or heavily impactful when realized. Regarding many other technologies not mentioned in this book, it is the hope of editors that readers would be able to find at least a clue how to get the necessary information through this book.

This book is available in both paper and electronic form. Although there are many colored figures in the e-book version, all of figures are in greyscale in the paper-book version. However, color versions of many figures are available on the CRC Press website (https://www.crcpress.com/9781498720045) and hard-cover book buyers can download them at no additional charge.

Siyong Kim and John Wong

Acknowledgments

The editors would like to cordially thank all the authors who have made an enormous effort to provide a book chapter that well describes both state-of-the-art and emerging technologies in radiation therapy.

The editors also would like to extend their thanks for the support of the Taylor & Francis team, particularly Francesca McGowan and Rebecca Davies who kept providing administrative help through the whole process of the project.

Lastly, the editors would like to further extend their thanks to their families for the endless support, encouragement, and patience.

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The mission of IOMP is to advance medical physics practice worldwide by disseminating scientific and technical information, fostering the educational and professional development of medical physics and promoting the highest quality medical physics services for patients.

A World Congress on Medical Physics and Biomedical Engineering is held every three years in cooperation with International Federation for Medical and Biological Engineering (IFMBE) and International Union for Physics and Engineering Sciences in Medicine (IUPESM). A regionally based international conference, the International Congress of Medical Physics (ICMP) is held between world congresses. IOMP also sponsors international conferences, workshops and courses.

The IOMP has several programs to assist medical physicists in developing countries. The joint IOMP Library Programs supports 75 active libraries in 43 developing countries, and the Used Equipment Programs coordinates equipment donations. The Travel Assistance Programs provides a limited number of grants to enable physicists to attend the world congresses.

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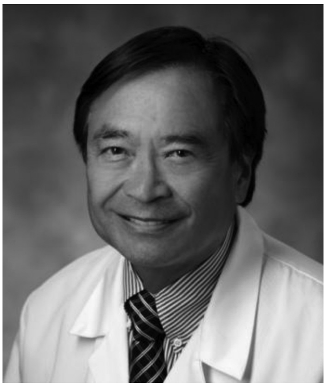
IOMP collaborates with international organizations, such as the World Health Organizations (WHO), the International Atomic Energy Agency (IAEA) and other international professional bodies such as the International Radiation Protection Association (IRPA) and the International Commission on Radiological Protection (ICRP), to promote the development of medical physics and the safe use of radiation and medical devices.

Guidance on education, training and professional development of medical physicists is issued by IOMP, which is collaborating with other professional organizations in development of a professional certification system for medical physicists that can be implemented on a global basis.

The IOMP website (www.iomp.org) contains information on all the activities of the IOMP, policy statements 1 and 2 and the 'IOMP: Review and Way Forward' which outlines all the activities of IOMP and plans for the future.

Editors

Dr. Siyong Kim is Professor and Director of Clinical Physics, Department of Radiation Oncology, Virginia Commonwealth University (VCU), Richmond, Virginia. VCU provides a full range of clinical services at the VCU Medical Center and its six satellite facilities. In addition, three medical physics education programs are offered: Medical Physics Graduate Program; Medical Physics Residency Program; and Medical Physics Certificate Program. Since joining VCU in 2013, he has been the Director of Medical Residency Program as well. He received a master's degree in nuclear engineering from Seoul National University, Seoul, Korea, in 1986. He entered the University of Florida, Gainesville, Florida, to study medical physics in 1993 and earned his PhD with a thesis on Modeling of a Multileaf Collimator (MLC) in 1997. Through the PhD project, he developed a software module of MLC for a commercial treatment planning system, introduced a more accurate equivalent square field formula for head scatter, and established a general solution for head scatter calculation especially in intensity-modulated radiation therapy (IMRT). Dr. Kim has performed research in the area of dose uncertainty estimation, patient motion management, and image guidance method, resulting in over 60 peer-reviewed journal articles and over 150 conference abstracts. He also has mentored students both nationally and internationally, served as either a member of editorial boards or reviewer for over a dozen scientific journals, published 12 book chapters, and published 1 report book. He has been actively involved in professional service including multiple American Association of Physicists in Medicine (AAPM) and IMPCB (International Medical Physic Certification Board) committees.



Dr. John Wong is Professor and Director of Division of Medical Physics in the Department of Radiation Oncology and Molecular Radiation Sciences at Johns Hopkins University School of Medicine.

Dr. Wong oversees the physics and dosimetry services of the department. Dr. Wong is the primary or contributing author of over 170 peer-reviewed scientific publications and 20 book chapters. He has been a principal investigator or co-investigator on 20 research initiatives funded by public agencies and industries. He is a co-inventor of the Active Breathing Coordinator, flat panel Cone-Beam CT, and the Small Animal Radiation Research Platform (SARRP) that have been commercialized as radiation therapy products for the clinical and research community.

Dr. Wong is a Fellow of the American Association of Medical Physicists, the recipient of the George Edelstyn Medal from the Royal College of Radiology, United Kingdom in 2001, and the awardee of the Edith Quimby Lifetime Achievement Award of the American Association of Physicists in Medicine (AAPM) in 2017. His current research focus is on molecular optical imaging for pre-clinical radiation research, robotic ultrasound imaging for Image-guided radiation therapy (IGRT), and informatics infra-structure for data sharing in radiation oncology. He is committed to advancing cancer treatment through education, research, and collaboration.

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CHAPTER 1

Recent Advances in Computed Tomography

Choonik Lee, Satoshi Kobayashi, Kosuke Matsubara, and Toshifumi Gabata

CONTENTS

1.1 INTRODUCTION

Since the first patient brain scan was performed in 1971, computed tomography (CT) has gained unmatched popularity in the medical imaging field. It is performed for close to 70 million cases in the United States alone in 2006 (Beckmann, 2006; Mettler et al., 2008, 2009; Schauer and Linton, 2009). The increased speed of the scan, especially with the multislice detector, has accelerated the adaptation of CT. In external beam radiation therapy, CT imaging has almost eliminated the need for the conventional simulator. The volumetric anatomical information that CT provides enables three-dimensional treatment planning, in which normal tissues can be spared while maximizing the dose to target volumes. Digitally reconstructed beam's-eye views from CT also provide critical anatomical information for treatment planning and daily patient setup (McShan et al., 1990).

CT images provide fast and robust morphological information but, more important, they also provide relative quantitative information of different tissues. For megavoltage photon and electron radiation therapy, the CT number-to-electron density or physical density relations have been used for accurate dose calculation within patients (Kijewski and Bjärngard, 1978; Parker et al., 1979; Cassell et al., 1981; McShan, 1987; Schneider et al., 2000). This CT number–to–density conversion is a required step due to the difference in the energies of diagnostic X-rays (typically around 100 kVp), which are far less than the energies of therapeutic beams that conventional medical linear accelerators produce.

With the advancement of the sixth generation multi-slice helical CT, it was possible to capture temporal displacements within the patient (Low et al., 2003; Vedam et al., 2003; Keall et al., 2004). This so-called four-dimensional CT (4DCT) enables the assessment of organ motion, especially for organ motion caused by respiration. Target volume encompassing the full extent of motion could be defined and used for radiation therapy treatment planning optimization (Underberg et al., 2004), further reducing the dose to nearby normal tissues.

There is no question that current CT technology provides invaluable morphological and radiological information that is essential to radiation therapy treatment calculation and image guidance; however, CT suffers from its own limitations compared to other imaging modalities, such as magnetic resonance imaging (MRI). Compared to MRI, which can provide excellent soft-tissue contrast without the use of ionization radiation, conventional CT has limited soft-tissue contrast and can impart non-negligible radiation exposure to patients. Its poorer contrast has been shown to result in less robust prostate contouring than MRI (Roach et al., 1996; Rasch et al., 1999). The inherent radiation exposure and its potential risk of secondary cancer is of concern (Brenner and Hall, 2007; Berrington de González et al., 2009; Mettler et al., 2009; Schauer and Linton, 2009; Pearce et al., 2012). Practice changes have been recommended for lowering the overall imaging dose as much as possible, especially for the pediatric patient group (Kalra et al., 2004; Goske et al., 2008, 2012).

In this chapter, we will discuss recent development in the field of multispectral CT, or dual-energy CT, which can provide improved soft-tissue contrast without additional radiation exposure, along with other recent exciting developments in CT.

1.2 DUAL-ENERGY CT

1.2.1 Background and Physics of Dual-Energy CT

It has been recognized since the inception of CT that dual-energy acquisition could improve tissue characterization by taking advantage of the energy dependency of photoelectric effects (Chiro et al., 1979; Millner et al., 1979), but dual-energy CT (DECT) has not been clinically implemented until recently because the technological requirements to achieve near-simultaneous acquisition were not available (Johnson et al., 2011; Coupal et al., 2014).

In typical clinical practice, X-ray tube voltages used in CT scanning range between 70 and 140 kVp. Due to the probabilistic nature of the bremsstrahlung production in the rotating anode target, the resulting X-rays have a broad spectrum ranging between 30 and 140 keV, depending on X-ray tube design. In this energy range, Compton scattering and photoelectric effects play dominant roles as the X-rays interact with human tissues. Soft tissues with low atomic numbers are not affected much with tube voltage selections because their K-shell binding energy values are not much different and are relatively low. For tissues with higher atomic numbers, however, the resulting image contrast is affected heavily by the selection of tube voltage because the contributions from photoelectric effects are accentuated by steep power functions of X-ray energy and atomic number. With dual-energy CT, it is possible to decompose the inherent contrast in attenuation coefficients as a linear combination of distinctive Compton scattering and photoelectric components (Saba et al., 2015).

For example, in the conventional CT energy range, calcium and iodine may result in similar attenuation. At a lower energy range, however, the attenuation of iodine is higher than that of calcium, thus making it possible to differentiate the two materials (Figure 1.1)

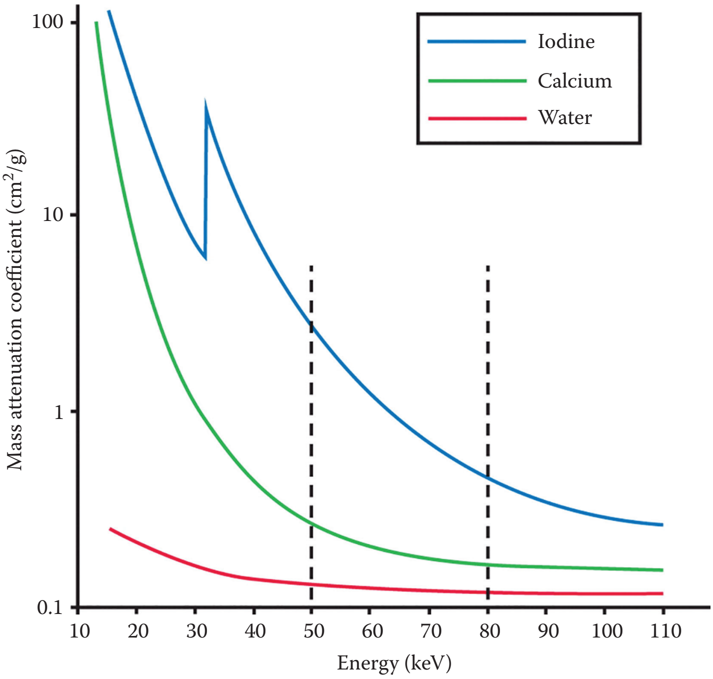

FIGURE 1.1 Mass-attenuation coefficients for iodine (blue), calcium (green), and water (red) on CT images obtained at two different energies (vertical dashed lines) shows that these materials can be characterized by comparing their attenuation at the lower energy with that at the higher energy. When dual-energy images reconstructed for 50 and 80 keV are compared, iodine demonstrates a greater decrease in attenuation than calcium does at the higher energy, whereas the attenuation of water remains more or less constant. (From Kaza, R.K. et al., *Radiographics*, 32, 353–369, 2012. With permission.)

(Kalender et al.. 1986; Kaza et al., 2012). This feature can be used to create virtual noncontrast images (contrast subtraction) along with the usual contrast-enhanced images from a single acquisition of DECT (Brodoefel et al., 2009; Toepker et al., 2012). This implies that overall patient exposure from DECT could be lower than the conventional contrast-enhanced CT, which typically involves two or more scans with and without contrast. This ability of material decomposition can enable the diagnosis of various conditions, including cancerous tissues, where conventional CT would fail to provide enough conspicuousness (Coursey et al., 2010).

The settings of 80 and 140 kVp are commonly used in DECTs because they provide enough difference and less overlap between the spectra produced with standard X-ray tube (Johnson, 2012). Newer generation DECTs, second-generation DECTs, may have a pair of 100 and 140 kVp sources where the spectral overlap is limited by applying additional filtering to 140 kVp source, resulting in better decomposition of materials (Primak et al., 2009).

Different approaches have been attempted by different investigators to achieve optimal decomposition. These approaches can be categorized as follows: (1) dual-source, dual-detector CT scanner (DSCT); (2) single-source, fast energy switching CT scanner; (3) single-source, dual-layer detector CT scanner; and (4) single-source with split-filter CT scanner. Figure 1.2 illustrates three different approaches.

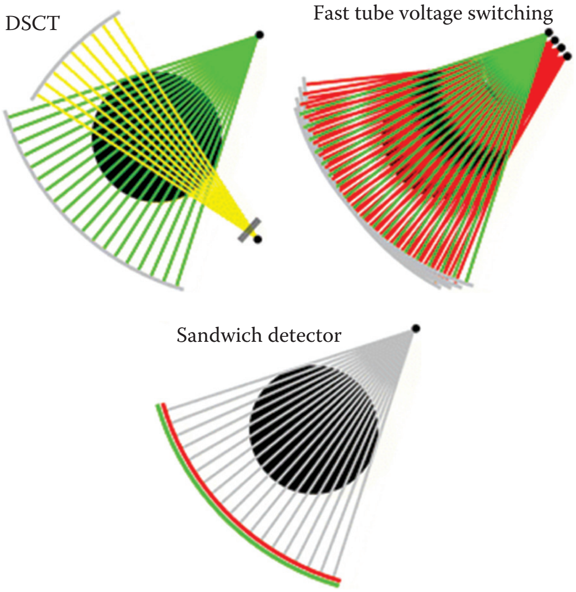

FIGURE 1.2 Different hardware approaches to dual-energy CT (DECT) imaging. In particular, three implementations are available: dual-source CT (DSCT), fast kilovoltage (kV) switching, and sandwich (dual-layer) detector techniques. (From Simons, D. et al., *Eur. Radiol.*, 24, 930–939, 2014. With permission.)